Title

A quantitative health impact assessment of urban greenspace and all-cause mortality across 1,041 global cities

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Abstract
Urban greenspaces are associated with improved health and climate resiliency. Large scale health impact assessments of urban greenspace and mortality have been limited to American and European cities. We estimated changes in mortality associated with observed differences in population-weighted greenest season normalized difference vegetation index (NDVI) between 2014-2018 and 2019-2023 across 1,041 global cities representing 174 countries. We used publicly available high-resolution satellite-derived estimates of NDVI and population, baseline disease rates from the Global Burden of Disease study, and a hazard ratio of the association between NDVI and all-cause mortality from an epidemiological meta-analysis. We found that urban greenspace varies substantially across cities (NDVI mean: 0.270, range: 0.072, 0.580) and by climate classification and geographic region. Despite modest global average changes in NDVI from 2014-2018 to 2019-2023, NDVI has changed by over +/-20% in individual cities. Median regional changes were largest in South-eastern Asia (-0.022), Sub-Saharan Africa (-0.010) and Eastern Asia (+0.014) and most stable in arid climates (<0.000). These changes were associated with a global median of 0.29 additional annual deaths per 100,000 in the 2020 population, ranging from 24.44 fewer to 21.84 more deaths per 100,000 across cities. NDVI is generally higher and more stable in European and North American cities, where epidemiologic studies and health impact assessments of NDVI and all-cause mortality have focused. Our results highlight large heterogeneity in urban greenspace extent and variability across global cities and the importance of characterizing the health implications of NDVI in more diverse contexts.

Introduction

Urban greenspaces (such as city parks and tree-lined streets) and blue spaces (like lakes, rivers, and coastlines) have been linked to improvements in human health and climate resiliency. Greenspace has been associated with improved mental and physical health, including reduced all-cause mortality.[1] While less studied, blue space has also been linked to improved health.[2] Urban green and blue spaces have also been associated with beneficial environmental outcomes such as better storm water management and heat regulation, increased biodiversity, and reductions in air pollution and ultraviolet radiation.[3–6] Greenspace has generally been the focus of urban nature policies and interventions, as it is more feasible to create than blue space.

Over half of the world's population lives in cities and this share is predicted to grow to two-thirds by 2050.[7] Urbanization has been accompanied by the pollution of natural resources, like air and water, and the destruction of natural environments. While cities are responsible for over 80% of global greenhouse gas emissions,[8] emissions per capita tend to be lower in cities than in less dense communities due to more efficient transportation, energy production, and land use.[9] In addition, cities can be effective entities of change and can provide a large enough scale to create meaningful change while remaining small enough to test policies that might not be feasible at a national scale. City-level interventions to increase urban nature offer a climate adaptation strategy with health advantages.

Studies linking greenspace to reductions in mortality have generally use the Normalized Difference Vegetation Index (NDVI). NDVI is a satellite-derived measure that uses red and near-infrared light waves to determine the health and density of vegetation.[10] Generally, negative values correspond to water, snow and ice, values near zero represent barren land and higher positive values indicate greener, denser vegetation. Two studies estimating the number of deaths associated with hypothetical changes in NDVI in European and American cities indicated that increasing urban greenspace can substantially reduce mortality. A 2021 study of 978 cities in 31 European countries found that if cities were to increase their NDVI to a level equivalent with the World Health Organization's recommendation of universal access to greenspace, 42,968 natural deaths could be avoided annually (95% CI: 32,296, 64,177) among adults.[11] A 2022 study of the 35 most populous American cities found that if overall NDVI was increased by 0.1, 38,000 deaths (95% CI: 28,640-57,281) could have been avoided in 2019 among those aged 65 years and older.[12] These studies suggest that urban greenspace can reduce premature mortality. However, a global health impact assessment is needed to characterize the potential health benefits from increasing greenspace across a broader range of climate and regional contexts.

In 2020, The Lancet Countdown began tracking urban greenspace across a global set of cities. The Lancet Countdown is an annual publication dedicated to tracking progress towards the goals of the Paris Agreement and documenting the health implications of climate change.[13] We updated the Lancet Countdown methodology to capture population at a finer scale (100m instead of 1km resolution) and to remove surface water from the urban greenspace calculation. We further conducted a health impact assessment of the increases or reductions in deaths associated with changes in urban greenspace over time across the 1,041 global cities included in the Lancet Countdown's greenspace analysis. We characterized urban greenspace across these cities from 2014 to 2023 and estimated the changes in mortality associated with differences in greenspace between two five-year periods, 2014-2018 and 2019-2023. The results of this study can be used to compare greenspace changes over time and associated health implications across cities globally.

Methods

We estimated peak seasonal urban greenspace using population-weighted NDVI from 2014 to 2023, in 1,041 cities across 174 countries. We then estimated the mortality change in each city associated with the difference in NDVI between two five-year periods, from 2014-2018 to 2019-2023. We defined urban extents using the Global Human Settlement Urban Centre Database (GHS-UCDB), which provides a consistent methodology based on population and remote sensing data.[14] Cities were included if they were the most populous in their country or had over 500,000 inhabitants. Twenty-two small, mainly island, countries did not have cities in the GHS-UCDB and were not represented in the analysis (see appendix List S1, for a complete list).

Population-weighted greenest season NDVI

For NDVI, we used Landsat 8 satellite imagery, accessed through Google Earth Engine (GEE). Landsat data is available at the 30m resolution with new images captured approximately every 16 days for a given location. To remove cloudy pixels, we used the "Landsat.simpleComposite" algorithm from GEE. We used the Joint Research Commission (JRC)'s Landsat-derived global surface water dataset (30m resolution) to exclude pixels that were classified as "permanent water."[15] We used the 2015 JRC dataset to mask water pixels in the 2014-2018 images and the 2020 dataset to mask water pixels in the 2019-2023 images.

We used Rojas-Rueda et al. (2019)'s meta-analysis to define the epidemiologic relationship between increased NDVI and reductions in all-cause mortality. This meta-analysis includes several large cohort studies in Spain, Canada, and Australia that defined greenspace using the average NDVI value from the greenest season.[16–18] We therefore calculated the population-weighted greenest season NDVI to align with this metric. After removing water pixels, we calculated pixel-level NDVI averages for each season: December 1 of the previous year through February 28, March 1 through May 31, June 1 through August 31, and September 1 through November 30. We averaged all Landsat images within these time periods. We combined our pixel-level average seasonal NDVI estimates with gridded population data from JRC's 100m Global Human Settlement Layer to calculate a population-weighted seasonal average NDVI for each city (Equation 1):

$$\text{Equation 1: } \frac{\sum_{i=1}^{n}(\mathrm{NDVI_i} * \mathrm{population_i})}{\sum_{i=1}^{n}(\mathrm{population_i})}.$$

We used the 2015 population distribution for years 2014-2018 and the 2020 population distribution for years 2019-2023. For each year, we selected the highest population-weighted seasonal average NDVI, representing the greenest or peak season, for each city.

Health Impact Assessment

We used a linear health impact function to estimate the annual change in premature deaths (more or fewer) associated with changes in urban greenspace (decreases or increases) following previous health impact assessments of greenspace on mortality.[19,20] The health impact equation is a function of baseline mortality rates, population, changes in greenspace exposure, and the exposure-response function between NDVI and all-cause mortality. We first calculated the population attributable fraction (PAF) of deaths related to insufficient green area using the hazard ratio (HR) of the protective effect of NDVI on all-cause mortality raised to the scaled change in population-weighted greenest season NDVI ($\Delta NDVI$) in each 100m pixel (i) (Equation 2):

$$\text{Equation 2: } PAF_i = 1 - \frac{1}{HR^{\frac{\Delta NDVI_i}{0.1}}}$$

We used the difference between the average 2014-2018 and 2019-2023 population-weighted greenest season NDVI to define changes in urban greenspace ($\Delta NDVI_i$). We opted to use a five-year average rather than compare individual years, because we observed large inter-annual variability in NDVI. We scaled the change in greenspace ($\Delta NDVI_i$) by 0.1 (Equation 2) because we used a meta-analysis of the association between NDVI and adult all-cause mortality, which found a pooled hazard ratio of 0.96 (95% confidence interval (CI): 0.94, 0.97) for each 0.1 increase in NDVI within 500m of a person's home.[21]

We then summed across each 100m pixel (i) to calculate the annual greenspace related mortality burden change in each city ($\Delta mortality$) using 2020 country-level baseline mortality rates (y_0) from the Global Burden of Disease (GBD) 2021 study,[22] 2020 gridded population estimates (pop_i) from JRC,[23] and the population attributable fraction (PAF_i).

$$\text{Equation 3: } \Delta mortality = \sum (y_0 * pop_i * PAF_i),$$

Urban area groupings

We categorize cities by geographic region using the United Nations Statistical Division sub-regional definitions (Fig. S1)[24] and by climate region using the Köppen-Geiger Climate Classification System (Fig. S2).[25] The sub-regional definitions break continental regions into smaller groups and are used by the United Nations in publications.[24] The Köppen-Geiger Climate Classification System divides the climate into five broad categories based on monthly precipitation and temperature and has been used to understand global vegetation patterns.[25]

Results

Globally, the annual average population-weighted greenest season NDVI has remained relatively consistent over the past decade (Fig. 1). The lowest global average in this period was 0.276 (years 2018 and 2023) and the highest was 0.281(years 2014 and 2015). The average range in annual NDVI over the past decade across all cities was 0.056. Some cities' NDVI ranged less than 0.01 over the last ten years, while others experienced swings of over 0.2. Regionally, cities in Sub-Saharan Africa, Eastern Asia, and Southern Asia had larger inter-annual variation, with an average decadal range in NDVI of ~0.07, while cities in Northern Africa and Central Asia generally show a flatter trend (range in 10-year annual NDVI: ~0.03). NDVI has remained comparatively stable in arid cities, with an average city 10-year range of 0.037, about half that of cities in other climate zones. All climate classifications and roughly half the geographic regions had individual cities with changes in NDVI of over 0.1 from 2014-2023. Considering the percent change in annual average peak season NDVI (Fig. S3), the greenest year of the past decade was over 20% higher than the least green year in roughly half of all cities.

Figure 1. *Population-weighted greenest season average Normalized Difference Vegetation Index (NDVI) from 2014-2023 by geographic region. Each thin line represents an individual city within the geographic region, while each thick line shows the average NDVI for all cities in that region, colored by climate classification.*

The average population-weighted peak season NDVI varies greatly across global cities (Fig. 2). In the most recent 5-year period, the global average greenest season NDVI was 0.270, ranging from 0.072 to 0.580 across cities. Peak season NDVI is correlated with geographic region (Fig. S4) and Köppen-Geiger climate classification (Fig. S5). Peak-season 2019-2023 NDVI was highest on average in Melanesia (0.417), North America (0.384), and most of Europe including Eastern (0.354), Northern (0.350), and Western (0.346) Europe. Western Asia and North Africa were the least green, with NDVI averages of 0.149 and 0.175 across their cities, respectively. In terms of climate classification, the average greenest season NDVI for 2019-2023 was 0.193 in arid, 0.281 in temperate, 0.319 in tropical, and 0.327 across continental cities.

Globally, the five-year greenest season average NDVI decreased slightly from 0.279 in 2014-2018 to 0.270 in 2019 to 2023, with an average city-level percent change of -0.46%. However, this relatively small global change masks large differences across individual cities. The percent change between these two periods ranged from -22.29% to 29.38% across the 1,041 cities.

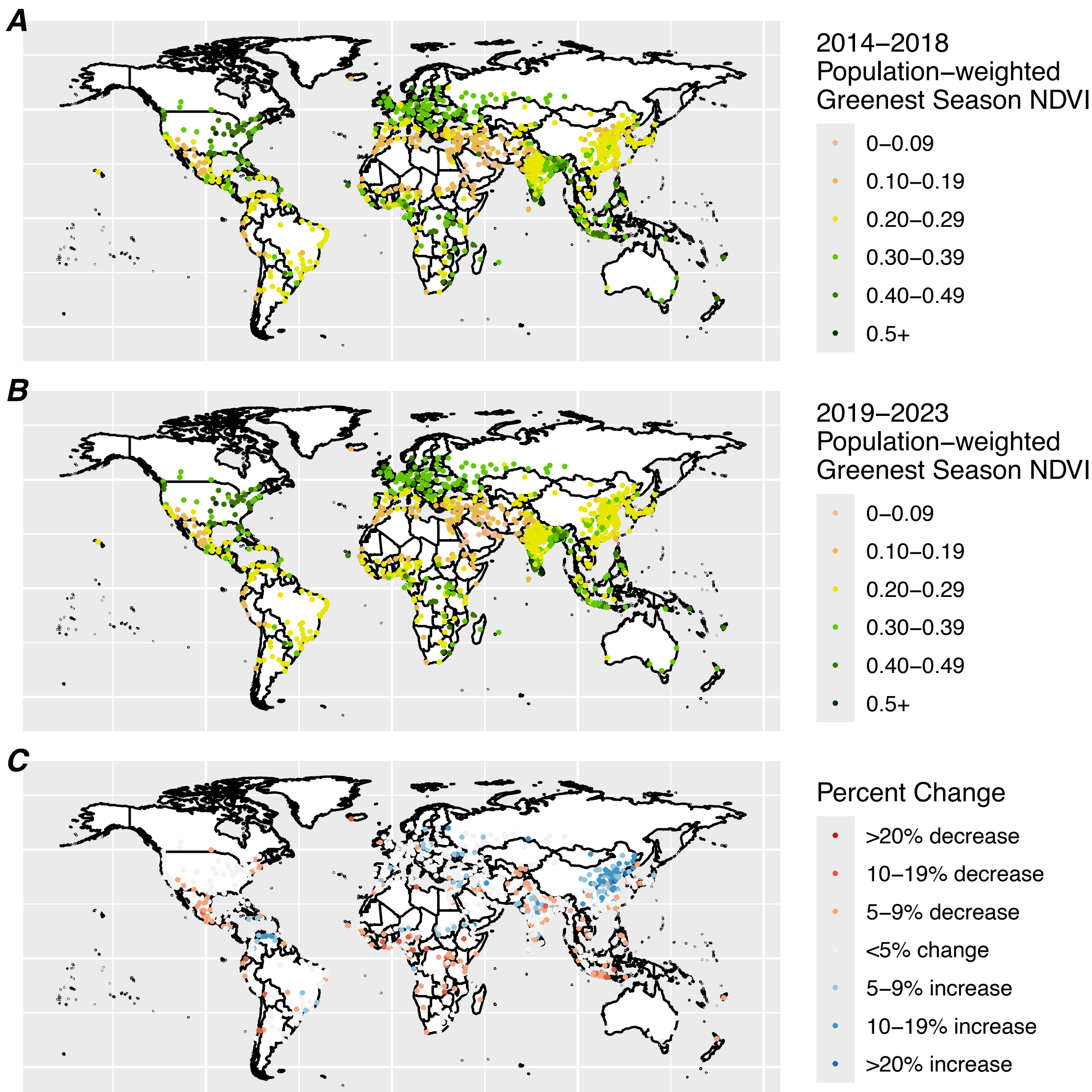

Figure 2. *Average population-weighted greenest season Normalized Difference Vegetation Index (NDVI) for 2014-2018 (panel A) and 2019-2023 (panel B) and the percent change between the two time periods (panel C) for 1,041 cities globally.*

Regional NDVI averages across the two 5-year periods were relatively stable (Fig 3A). The median regional NDVI changed by more than 0.01 in only four geographic regions: Melanesia (-0.018), South-eastern Asia (-0.022), Sub-Saharan Africa (-0.010) and Eastern Asia (+0.014). The regional range of absolute changes in NDVI ranged from 0.028 in Southern Europe to 0.095 in Eastern Asia. Every region had cities that became greener and others that became less green from 2014-2018 to 2019-2023.

There was a similarly large spread within each region and notable differences across regions in the percent change in NDVI between 2014-2018 and 2019-2023 (Fig. 3B). The median percent change was greater than 5% in South-eastern Asia (-6.3%) and Eastern Asia (+6.2%). Sub-Saharan Africa had 6 of the 10 cities with the largest percent decreases in NDVI from 2014-2018 to 2019-2023. By contrast, 39 of the top 50 cities with the greatest percent increase in NDVI between these two time periods were in Eastern Asia. The relative magnitude of percent changes in NDVI generally mirrored changes in absolute terms.

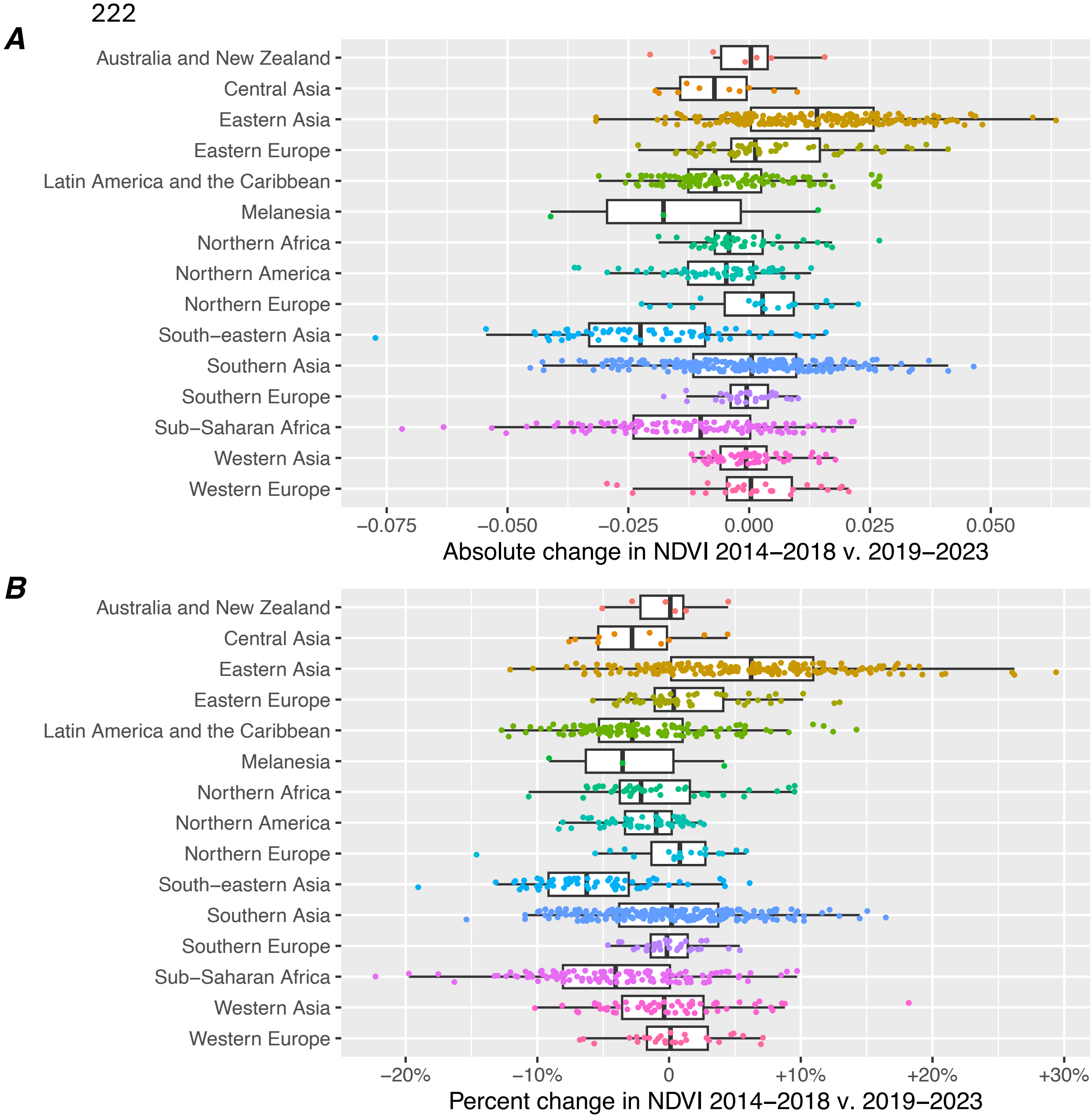

Figure 3. *Change in average population-weighted greenest season Normalized Difference Vegetation Index (NDVI) from 2014-2018 to 2019-2023 in absolute (panel A) and relative (panel B) terms, by geographic region, for 1,041 cities globally.*

In general, cities classified as "Arid" by the Köppen-Geiger climate classification did not experience large changes in NDVI between the two time periods (median change: <0.000, range:

-0.046, 0.041) (Fig. 4A). The tropical climate classification became less green from 2014-2018 to 2019-2023, with a median city change of -0.010 (range: -0.077, 0.033), while continental cities generally increased in NDVI (median: 0.006, range: -.035, 0.048). Like arid cities, the median change in urban greenspace across temperate cities was close to zero (-0.001), with increases and decreases across individual cities (range: -0.045, 0.064).

The median percent change in population-weighted peak season NDVI was -0.01% in arid, -0.2% in temperate, +1.7% in continental, and -3.1% in tropical cities (Fig. 4B). Temperate cities had the largest spread in relative terms (44.8 percentage points) compared to continental (20.8), tropical (37.4) and arid (29.1) cities. NDVI decreased by about 20% in three tropical cities (Goma, Democratic Republic of the Congo; Yaounde, Cameroon; and Mataram, Indonesia) and increased by over 20% in three temperate cities (Zhengzhou, Shiyan, and Zhenjiang, China) and two continental cities (Pyongyang, North Korea; and Rizhao, China).

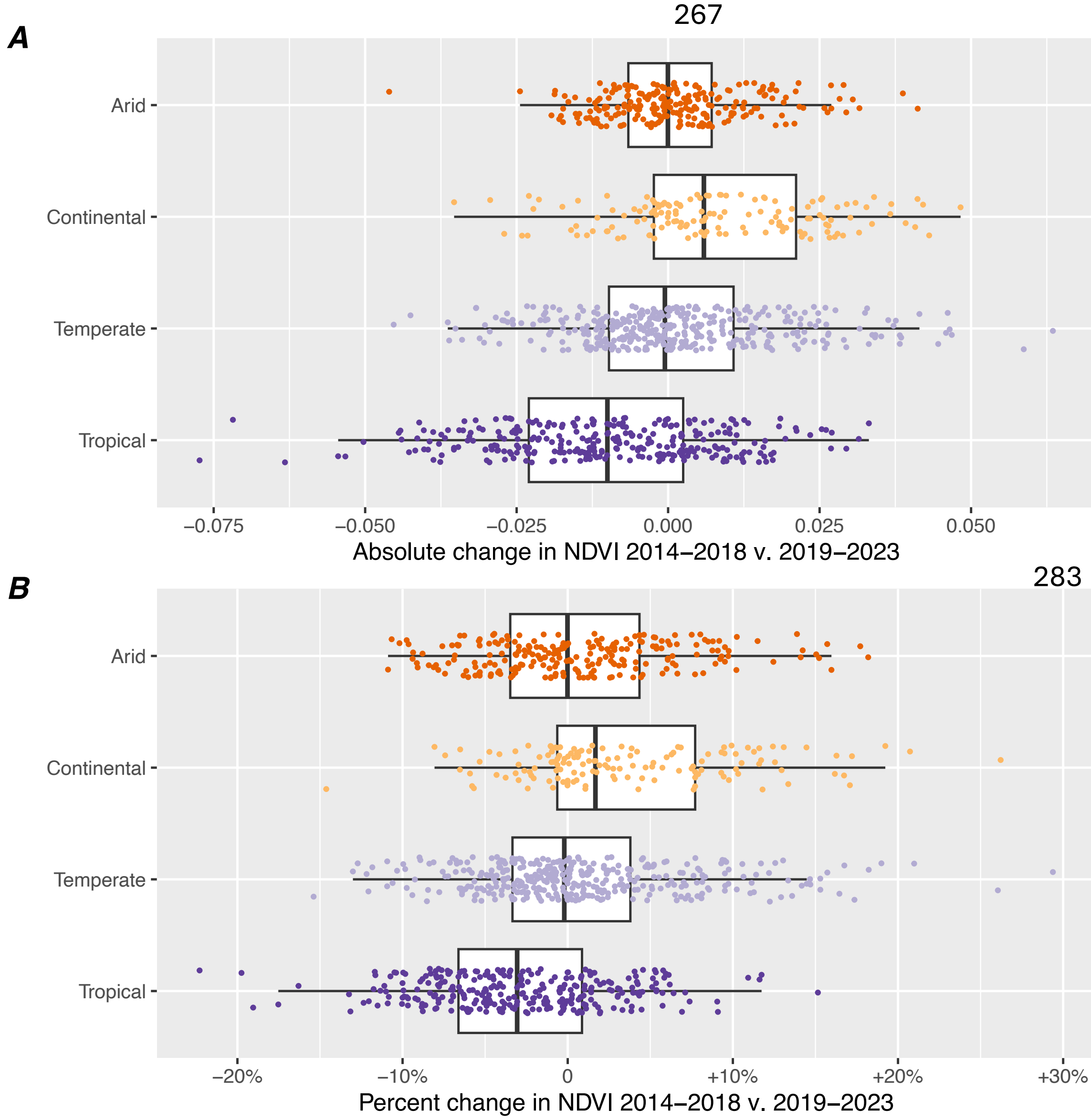

__Figure 4.__ Change in city average population-weighted greenest season Normalized Difference Vegetation Index (NDVI) from 2014-2018 to 2019-2023 in absolute (panel A) and relative (panel B) terms, by Köppen-Geiger climate classification. One city classified as "Polar" was removed from the figure (El Alto, Bolivia; change in NDVI: -0.013 (-10.5%)).

Globally, NDVI changes from 2014-2018 to 2019-2023 were associated with an estimated mean of 0.19 (95% CI: 0.15, 0.25) more all-cause premature deaths per 100,000 annually to the 2020 population (Fig. 5). The premature mortality impact from urban greenspace change was not evenly distributed around the world (Fig. 5A). Changes in associated deaths closely mirrored trends in NDVI, with the largest reductions in Eastern Asia. Eastern Asia had a median reduction of 4.72 (IQR: 8.52, 0.13) annual premature deaths per 100,000 population, though even within this region there was substantial variation across cities, ranging from 21.25 fewer premature deaths per 100,000 in Shiyan, China to 13.72 more premature deaths per 100,000 in Hiroshima, Japan. Southeastern Asia and Sub-Saharan Africa had the highest increase in health burdens, with medians of 6.0 (IQR: 2.42, 9.44) and 3.42 (IQR: -0.06, 7.35) more deaths per 100,000 respectively. Substantial intra-regional variation existed for these regions as well- ranging from 3.75 fewer deaths to 21.84 more deaths per 100,000 in South-eastern Asia and from 9.04 fewer deaths to 21.45 more deaths per 100,000 in Sub-Saharan Africa.

Considering NDVI-associated mortality changes by climate classification, the median change in mortality associated with changes in NDVI was 0.01 fewer (range: 12.90 fewer to 12.14 more) deaths per 100,000 among arid cities (Fig. 5B). Temperate cities were similarly fairly evenly distributed between those with fewer and more deaths associated with changes in NDVI but had a larger spread than arid cities. Temperate cities had a median change of 0.21 more (range: 21.15 fewer to 14.83 more) deaths per 100,000. Tropical cities became, on average, less green over the past decade and had a median of 2.84 more (range: 10.97 fewer to 21.84 more) associated deaths per 100,000. In contrast, continental cities became slightly greener on and had a median of 2.44 fewer (range: 24.44 fewer to 14.50 more) associated deaths per 100,000. The spread across all climate classifications spanned reductions and additions in deaths. The absolute number of deaths per city associated with changes in NDVI are presented in the appendix (Fig. S6). Region- and climate classification-wide total attributable deaths per 100,000 and the corresponding 95% CIs can be found in the appendix (Fig. S7, Table S1-S2). Individual city mortality estimates are also provided (Table S3).

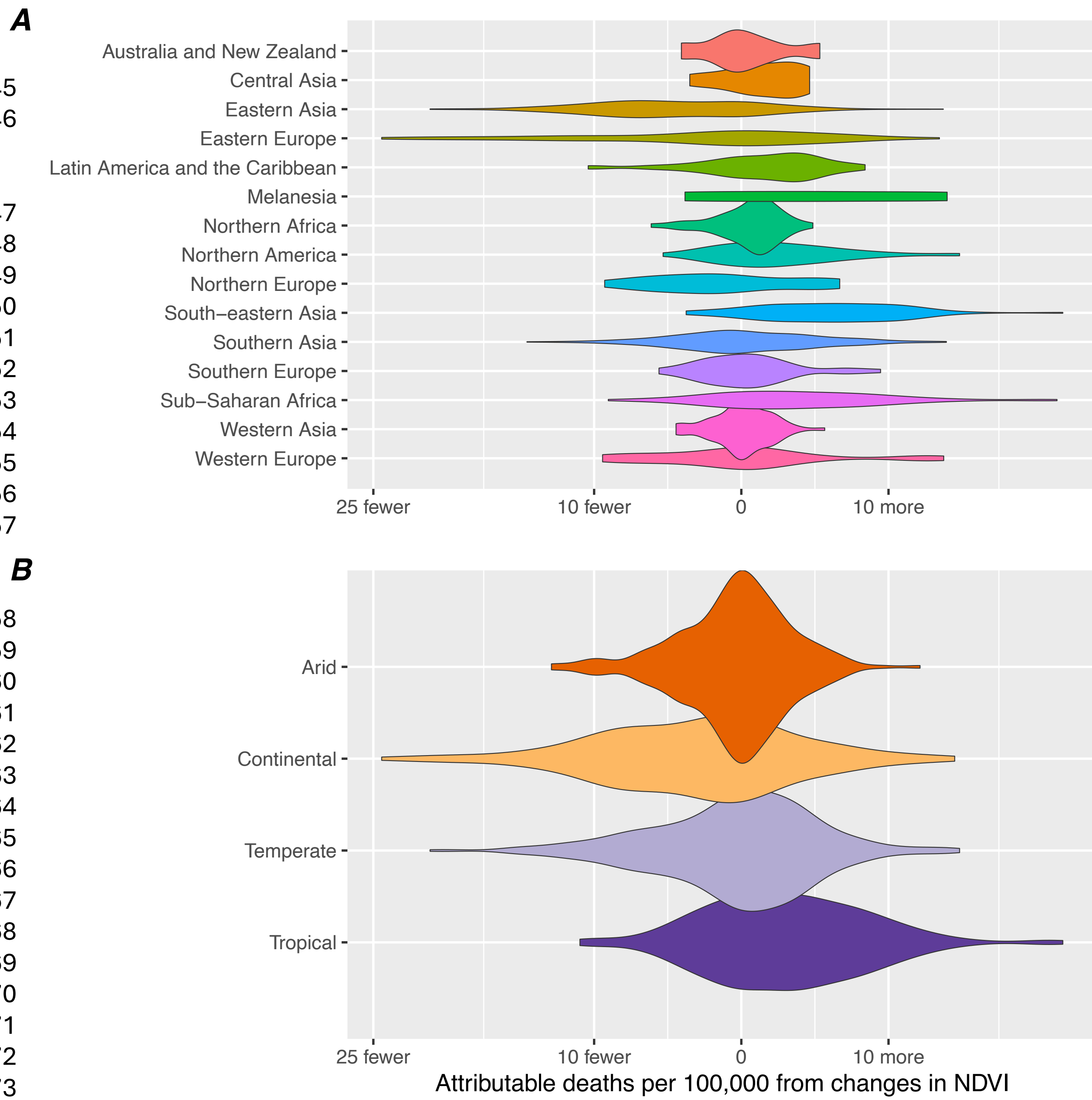

Figure 5. *Associated changes in city-level mortality per 100,000 population from changes in average population-weighted peak season Normalized Difference Vegetation Index (NDVI) from 2014-2018 to 2019-2023 to the 2020 population, by geographical region (panel A) and climate classification (panel B). One city classified as "Polar" was dropped from panel B (El Alto, Bolivia, 4.78 more deaths per 100,000 population).*

Discussion

Urban greenspace varies greatly (NDVI mean: 0.270, range: 0.072, 0.580) across the 1,041 cities studied and is related to region and climate classification. Overall, urban greenspace has remained stable from 2014-2018 to 2019-2023. However, individual cities experienced over 20% changes in city average NDVI in either direction. Regionally, NDVI changed over 5% in South-eastern Asia (-6.3%) and Eastern Asia (+6.2%), while cities classified as arid were the most stable. We estimated that NDVI changes from 2014-2018 to 2019-2023 were associated with an average of 0.19 (95% CI: 0.15, 0.25) additional deaths per 100,000 across the 1,041 cities. While the global estimate showed almost no change, mortality changes associated with urban greenspace ranged widely, with over 100-fold higher and lower death rates across individual cities.

Our urban greenspace estimates align closely with previous work using a similar spatial scale and inclusion criteria and are considerably lower than a study using a coarser spatial resolution and more inclusive urban definition. Brochu et al. quantified urban greenspace across the 35 most populous U.S. cities using census tracts as the unit of analysis, which are generally spatially analogous to our 100m pixels in urban areas.[12] They reported a mean NDVI of 0.35-0.40 between 2000-2019, which aligns well with our population-weighted peak season NDVI estimates of 0.39 in 2014-2018 and 0.38 in 2019-2023 across all North American cities. Barboza et al. estimated an average baseline NDVI of 0.52 (range: 0.11-0.72) across 978 European cities.[11] Our baseline NDVI estimates were substantially lower, with a mean estimate of 0.33 (range: 0.13, 0.46) across European cities. Barboza et al. averaged NDVI using a 300m buffer around each 250m pixel, which could partially explain this discrepancy. In previous Lancet Countdown reports, NDVI was averaged to the 1km resolution, which produced higher estimates of NDVI, with a WHO European region average of 0.37.[13] Coarser resolution data may increase the NDVI estimate in dense urban centers, by averaging values from greener areas outside the city center. Furthermore, we limited the analysis to cities with over 500,000 inhabitants, while the Barboza et al. study used the Organization for Economic Cooperation and Development city definition, which includes urban areas with as few as 50,000 residents. Smaller cities may be greener due to the need for less infrastructure.

Our health impact estimates differ from past work, as we compare historical changes (both negative and positive), whereas previous studies have looked at the impact of hypothetical additions in greenspace. Brochu et al. estimated that 0.1 increases in NDVI were associated with 200, 170, and 150 fewer deaths per 100,000 across 35 American cities among those 65 and older in 2000, 2010, and 2019, respectively. We estimated that NDVI changes were associated with an average of 2.67 more deaths per 100,000 across the entire North American population. We found that NDVI decreased over our study period, explaining the difference in sign of our results. Barboza et al. estimated health impacts of increasing NDVI to the World Health Organization's recommendation of universal access to greenspace and reported large variability across European cities ranging from 1-59 fewer deaths per 100,000 inhabitants among adults 20 years and older. Our health impact estimate of the associated mortality change from NDVI changes across European cities was 0.41 fewer deaths per 100,000 (range: 24.44 fewer to 13.75 more).

There are several key limitations to our study. We use one exposure-response function globally that is based on primarily European and North American populations. The relationship between NDVI and all-cause mortality may be related to many factors that also vary by region. City walkability (safety, pedestrian infrastructure, traffic, etc.), time spent at home where we have measured their exposure (employment type, leisure time, etc.), and other environmental hazards (heat, air pollution, noise, etc.) is likely different globally and could influence the relationship between greenspace and mortality. Individual factors like age, socioeconomic status, and gender might impact the health benefits of greenspace. While the meta-analysis we used controls for many of these city and individual factors, the populations included might not be generalizable globally. Additionally, greenspace is relatively high in North American and European cities, meaning that fewer data points contribute to the exposure-response curve at lower NDVI levels. We used NDVI to measure urban greenspace, which has limitations. NDVI is the most common metric used in epidemiological studies, because of its fine spatial and temporal resolution, which lends itself particularly well to longitudinal studies and urban settings. However, NDVI is a function of the greenness of vegetation, which can miss important factors influencing usability such as land ownership, perceptions of safety, and infrastructure. Finally, we used baseline mortality rates from the Global Burden of Disease study, which were largely available at the country level, and may not be reflective of baseline mortality rates in cities.

We found substantial inter-annual variation in NDVI, particularly in cities outside of arid climate zones. Differences in NDVI between two individual years are therefore more likely to reflect weather patterns than city-wide efforts towards urban greening. To account for these cyclical patterns, we compared differences between two 5-year periods. These time periods roughly align with the Lancet Countdown's reporting, which has published greenspace exposure dating back to 2015, while creating two equal time periods and using the latest available data. While our exposure definition limits the influence of weather on our NDVI estimates, the inter-annual variation highlights difficulties with using NDVI for health impact assessments. Recent efforts to increase urban greenspace may be attenuated in our study by using five-year averages.

Conclusion

We found large inter-annual variability in NDVI, likely driven by a mix of weather, climate change, urban development, and efforts to increase urban greenspace. Globally, urban average NDVI remained relatively stable from 2014-2018 to 2019-2023. However, we observed NDVI changes in individual cities of over 20%. Urban NDVI changes between these two periods were associated with a median of 0.29 more deaths per 100,000 globally each year, ranging from 24.44 fewer to 21.84 more deaths per 100,000 across the 1,041 cities. Future research should explore alternative measurements to NDVI and target levels of urban greenspace for healthy and sustainable cities.

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